Robotics and Telepresence for Moon Missions

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MOON PROGRAMME

An integrated moon program has often been proposed as a logical next step for today's space efforts [1,2,3]. In the context of preparing for the possibility of launching a moon program, the European Space Agency is currently conducting an internal study effort which is focusing on the assessment of key technologies. Current thinking has this moon programme organized into four phases.

Phase I of these phases will deal with lunar resource exploration. The goals of this phase of the programme would be to produce a complete chemical inventory of the Moon, including oxygen, water, other volatiles, carbon, silicon, and other resources. A high resolution topographical mapping of the surface of the moon will also conducted. This phase will be accomplished through lunar polar orbiting satellites, possibly equipped with tethered instruments, and a small lander craft. This small fixed lander(s) shall be equipped with a robotic arm to conduct some in situ analysis.

Phase II of the moon programme will establish a permanent robotic presence on the moon via a number of landers and surface rovers. These rovers could continue the chemical analysis, conduct a geophysical survey, and deploy and service various instruments. Some instrumentation would also be located on the fixed landers. Control of these rovers, and the robotic elements of the landers, will generally be handled through remote control from the earth. Telepresence will play a vital role.

Phase III will extend the second phase and concentrate on the use and exploitation of local lunar resources. Automated oxygen production pilot plants, robotic construction investigations, and life support and biological experimentation could all be elements of this phase. In addition to this preliminary astronomical observation is foreseen. A robotic rover might deploy a Very Low Frequency (VLF) Array, probably on the farside of the moon.

Phase IV will be the establishment of a first human outpost. Some preliminary work such as the building of the outpost and the installation of scientific equipment will be done by unmanned systems before a human crew is sent to the moon. Once there, the astronauts will be able to conduct experiments and geological investigations, as well operate the astronomical telescopes and imple-

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ment the oxygen production plant. To assist the human crew with these tasks, several robotic assets are foreseen.

ROBOTIC MISSIONS

Any near to mid-term European moon programme will undoubtedly be restricted to unmanned missions. One cannot expect the manned Phase IV of the moon programme to begin before 15 or 20 years from now. For this reason the area of lunar robotics and telepresence is considered to be critical.

Missions for lunar surface robotics can be grouped into the following five general profiles:

Simple In Situ Analysis Missions

These missions involve such tasks as operation of imaging cameras, spectrometry, temperature probing, and regolith sample analysis. These missions can generally be accomplished from a fixed lunar lander. A robotic arm attached to the lander could accomplish the tasks of placing sensor heads into the ground, and acquiring small surface samples for analysis by equipment on board the lander. This robotic arm would be controlled remotely from the ground via a telepresence interface to execute its tasks. In a similar fashion the camera pointing and focusing could be accomplished via telepresence.

Instrument Deployment Missions

Scientific Sensors and Stations will need to be deployed at various locations on the moon. These could range from simple thermal probes, to dipoles and seismic stations, to complex telescopes. While small probes could be deployed at a considerable distance from a fixed lander (10s of metres) by harpoon ejection devices and tether instrument deployment crawlers, larger instrument packages will require sophisticated rovers to deploy them at distances up to several hundreds of kilometres from the landing site. Simple deployment functions could occur relatively autonomously, with perhaps supervisory control from the earth. The control of more advanced deployment sequences, such as those involving complex scientific station deployment via a multifunction rover, will call for a more sophisticated control scheme of telepresence by earth-based human operators.

Geological Investigation Missions

These missions will involve the use of mobile rovers to map up terrain over long distances, and also includes the acquisition of samples of interest and the possible return of them to a fixed analysis station, or to return capsule destined for ground laboratories. Due to the investigative nature of this class of missions, human judgement will certainly be constantly required. A good virtual reality interface for the ground based operators is very desirable.

Engineering Support Missions

These missions can be accomplished by a monitoring and servicing vehicle, which will execute such tasks as visual inspection and servicing of installations, selection of suitable landing sites for future missions based on safety criteria, operation of beacon to guide incoming landers or rovers, cargo transportation, communication back-up, etc. Such a monitoring and servicing vehicle will be need both automated capabilities and the ability to be remotely controlled from the ground.

Construction Missions

The final group of robotic missions are those that entail the setup and construction of equipment on the lunar surface. This could be the assembly of communication equipment such as a large, possibly inflatable, dish for ground communication, or an antenna tower for surface communication with rovers. The assembly of the critical elements of a manned lunar outpost before the arrival of the human crew is another task to be accomplished in such missions. Various robotic elements will be required in these construction missions, and various control options will be required. If future manned missions are imminent, capability for future control by crew on the lunar surface should also be considered as a design requirement for these robotic systems.

MOBILITY ISSUES

Most lunar missions will have requirements to move various items from one location on the Moon to another. These items will range from simple experiment packages which have to be deployed at a distance of a few metres from an initial fixed lander, to large volumes of cargo that will be transported from one side of the Moon to the other during advanced base operations.

A critical component of the earlier unmanned segments of a Moon exploration and utilisation programme will be mobile lunar rovers. An analysis and evaluation of possible mobility methods for these rovers has been conducted as a comparative trade-off between wheels, tracks, and legs as mobility mechanisms [4].

Studies have shown that conical wheels are better suited to climb over obstacles than regular ones, and thus are most desirable for lunar surface vehicles. Wire mesh wheels cause less dust levitation, and therefore are desirable for vehicles carrying instrumentation that is very dust sensitive. Unfortunately these wire mesh wheels also have less grip with the surface. With regard to number of wheels on the rover, six seems to be the optimal compromise which maximises performance criteria, such as manoeuvrability and climbing ability, and minimises complexity of the entire system.

Tracks on the other hand have less surface slip than wheels, and a much higher performance on loose regolith. The disadvantage of tracks is that they have the risk of clogging with lunar dust, as well as having inherent mass and complexity penalties associated with their designs. For these reasons it is not recommended that lunar rovers, which have to operate in the dusty, atmosphereless moon environment, and also should be as reliable and light-weight as possible, be equipped with tracks as their propulsion mechanism.

Legged locomotion is currently a very immature technology, and is not considered to be developed to the level where its use on lunar systems is realistic. However, in theory, legged locomotion could offer good terrain adaptability with high performance in rough terrain and a minimum of locomotion power consumption. Such a system would require active stabilization with sophisticated attitude sensors, and also would require high computing effort for trajectory planning and control. Skis could improve performance on sandy terrain by adding some weight distribution. In general legged locomotion could become the method of choice for lunar surface transportation of the future, but is unadvisable for missions being planned today.

Displacement from one point on the moon to another via mechanical hoppers was also examined, and pogo and anthropomorphic designs were considered. While these concepts are theoretically interesting, the control problems inherent in keeping such systems upright are significant. For this reason such methods are not recommended. Furthermore, if extension to crew systems is attempted, the tolerance of the human vestibular system to the repeated accelerations could prove unacceptable.

Chemical or rocket hoppers were examined, but were found to be only interesting in the context of large displacement for heavy cargo in a mature Moon base(s) scenario. Engine gimballing and throttling will be required. These systems depend on similar technologies as lunar landers, and possibly could be evolved from the technologies developed for a future lander.

Tethered crawlers are interesting as they could offload power and control to a fixed lander while they investigate/deploy instruments close by. Very light-weight crawlers could be built that could deliver a sensor head into the regolith a few metres away from a fixed lander. Tethered probes are also potentially interesting for scenarios where the interior of permanently shadowed crater is to be explored, as the power could be transmitted from a solar array located in the sun on the rim of the crater.

Ejected harpoons could also be used to deploy sensors from a lander. The energy may be delivered by a mechanical, electrical or chemical system. Tethered hooks could be ejected in similar ways, and could assist rovers to climb steep slopes, or escape from loose regolith.

CONTROL ISSUES

Robotic lunar rovers will be a key component of any European Moon exploration and exploitation scenario. These unmanned rovers will certainly encounter unexpected situations, including obstacles and rough terrain. The rover control must be divided between onboard computers, ground computers, and ground based human operators. This division must maximise rover performance, while minimising costs and risks.

Onboard computers have the advantage that they have no communication time delays to the rover, and thus can react to unexpected situations instantly, but have the disadvantage that they have mass and power restrictions, and are physically remotely located, making design errors difficult to rectify.

Ground based computers do not suffer from mass and power restrictions, and thus can carry out much more complex calculations, but have communication time delay to the lunar rover. The round trip time delay is about three seconds.

Control can also be handled by a human operator on the ground. This allows for a maximum of adaptability to unexpected situations, as well as the superior human information extraction capability from visual imagery. Unfortunately the communication time delay is also a handicap for the ground based human operator. Predictive displays could partially overcome this.

The task at hand involves finding the best distribution of the control functionality between the three locations, and assessing relevant technologies.

Four concepts of the distribution of autonomy for the rover have been developed [5], and are being used as a basis for further analysis. They are summarised here:

Concept I: Everything is controlled with the human in the loop. All control is handled remotely by a ground-based human operator, with the sole exception of low-level hardware control which will remain close to the controlled equipment on board the rover.

Concept II: Hazard detection is done autonomously. The detection and the putting of the rover in a safe state is done autonomously. The process of re-planning or hazard avoidance is done by the human operator. A hazard is defined not only as an obstacle, but also shadows, steep gradients, etc. The hazards applicable for a particular rover are dependent on the type of the rover.

Concept III: Trajectory planning is automated. The trajectory planner has as an interface the human generated path segments. Trajectory planning here is defined as the specification of how the path is to be followed in time, as well the conversion from task space coordinates to rover actuator space coordinates (axle speed for wheeled rovers, joint space for legged rovers).

Concept IV: Path planning is automated (i.e. the interface from the human is the specification of the goal location where the rover should go, and the path planning and all lower levels are done autonomously).

The above four concepts do not necessarily identify the place where the autonomous functionality has to be implemented. There remain two possibilities (on board the rover, and in a ground computer), which depend partially on the mission envisaged. While the onboard computer can react instantaneously to sensory input, the ground based computer can be much larger and carry out much more complex calculations.

The optimal control strategy is thus one that distributes control between the onboard computer(s), the ground-based computer(s), and the human operator who can execute either direct or supervisory control.

Virtual reality offers exceptional capabilities to enhance the remote rover control by ground based humans, but is not yet a fully mature technology area. In a virtual reality system, the human operator has complete sensory inputs which give him the feeling that he is (or is in) the remote robotic rover. The operator gives his control inputs in a natural way. For example, if he wants to look to the left, he moves his head towards the left, which causes the cameras on the rover to point to the left, and subsequently for the correct image to be projected on the head mounted display worn by the operator. Such systems allow for a very high or total sense of immersion for the operator. Initial analysis has identified 300 kbit/s as the approximate bandwidth required for ground based control via a virtual reality type interface. This assumes stereo vision with advanced compression ratios of 10, and relatively low resolution video with 3 to 5 frames per second.

The round trip communication time to the Moon is limited by the speed of light. The minimum time is about 3 seconds. This makes realtime control of lunar rovers from the ground awkward and slow. One possible area that might form a partial solution to this is predictive display technology. The computer generated displays could predict the view from the rover three seconds ahead, based on an internal map, and the current motion of the rover. This technology area is still in the early research phase both in Europe and outside.

CONCLUSIONS

Robotic missions which form part of a moon program would typically involve such tasks as geological surveying, instrument deployment, and sample acquisition and analysis. The issues of mobility and control will be critical ones. The mobility technology used by the robotic system will depend on the task requirements. Wheeled locomotion is generally the preferred option for lunar rovers. Fixed robotic landers could use ejected harpoons or tethered crawlers to deploy sensor heads in the area surrounding the lander. The optimal strategy for any lunar robotic asset will involve distributed control, utilizing both human ground-based operators, and artificial intelligence located in various terrestrial and lunar computers.

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